Growth Mechanisms that Control InGaN Step Morphology

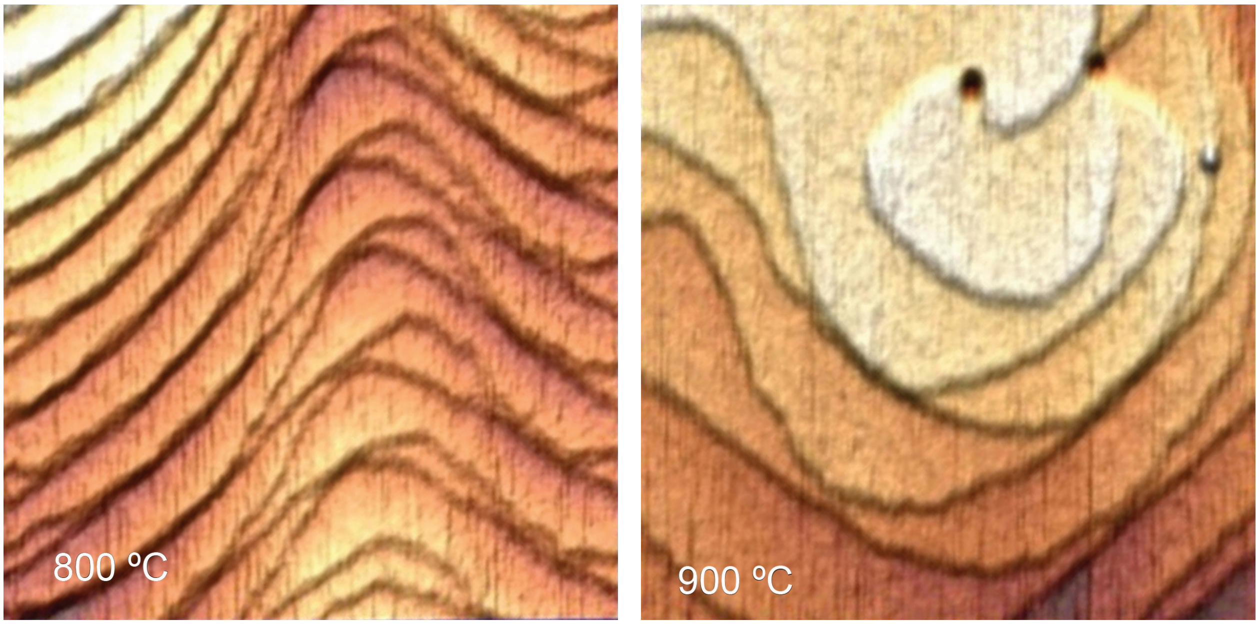

Figure 1: Atomic force microscopy images (1x1 µm) of InGaN/GaN surface morphologies when the GaN barriers are grown at T=800 °C (left) and T=900 °C (right).

Emission intensity from quantum well devices may be linked to morphology acquired during thin film growth

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In the U.S., more than 30% of all generated electricity is being used for lights in buildings and elsewhere. This is because traditional incandescent and fluorescent bulbs are not very efficient in converting electrical power into visible light. For this compelling reason, researchers worldwide are developing much more energy-efficient light emitting diodes (LEDs). Indium gallium nitride (InGaN) is an important compound semiconductor material that is being used to make bright, white-light LEDs. However, unlike other LED semiconductors, it typically contains a large number of defects when grown on flat sapphire substrates. Several theories have been proposed to explain how InGaN LEDs are able to operate despite the large defect density. While important details of these theories vary, the general consensus is that the process of electrical carrier localization allows the carriers to produce useful light; otherwise the carriers would migrate to defect sites where they undergo dark recombination and produce no light. Recently, Sandia has explored InGaN surface morphology in order to study how InGaN quantum well (QW) structures can be structurally tailored to possibly enhance localization and thereby improve LED brightness.

In one study, Sandia researchers grew 5-period InGaN quantum wells (QWs), which is the light-producing region of the LEDs, sandwiched between GaN barrier layers. The growth temperature can have a profound influence on the surface morphology of these materials. Examples of the temperature dependence are shown in Figure 1, where two otherwise identical QW structures were grown at the GaN barrier temperatures of 800 °C (left image) and 900 °C (right image). Comparison of these two images shows a difference in the step height and frequency morphology. For the film with GaN barriers grown at 900 °C, the steps heights are predominantly monolayer

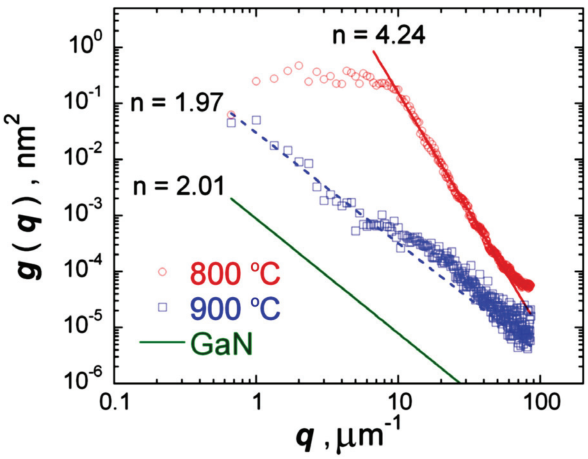

Figure 2: Calculated power spectral density, *g*, plotted as a function of the reciprocal length,*q*, for QWs where the GaN barrier is grown at either 800 °C (red) or 900 °C (blue). The *g*(*q*) for a high temperature grown GaN template is shown in green.

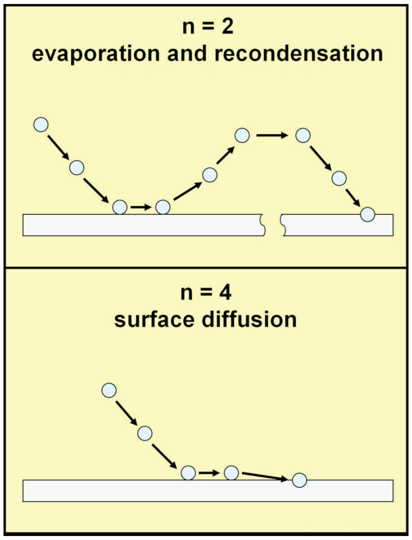

Figure 3: Depiction of the two surface smoothing mechanisms for InGaN/GaN at different GaN barrier growth temperatures. (Top) Evaporation and recondensation mechanism that occurs when growth T=900 °C. This leads to smoother surfaces with longer scale features (1-10 µm). (Bottom) Surface diffusion mechanism at growth T=800 °C. This leads to rougher surfaces with shorter scale features (10-100 nm).

(c/2 where c is the c-axis lattice constant) in height; while for the film with barriers grown at 800 ºC, there is an increase in the number of double-layer steps. The increase in the double-layer step frequency also means that the QW film with 800 ºC grown barriers is "rougher" than the QW film with 900 ºC grown barriers.

More advanced analysis of the images shown in Figure 1 can reveal how the surface roughness varies with distance and what mechanism is responsible for producing the observed morphology. For this analysis, the height-height correlation function or power spectral density, *g*, is calculated as a function of the reciprocal length scale, *q*. The root mean square roughness of the surface is obtained by taking the square-root of the sum of g(q) values over all q. A plot of g(q) vs. *q* is shown in Figure 2 for films with GaN barriers grown at 800 ºC (red) and at 900 ºC (blue), along with that of the blank, starting GaN template (green line). Notice that *g*(*q*) for the 800 ºC film are larger than those for the 900 ºC film, again indicating that the 800 ºC film is rougher.

Surface "smoothing" mechanisms during film growth can be discerned from the *g*(*q*) power dependence, n, following the work of Conyers Herring in 1950 [1]. For the 800 ºC QW sample, *n*=4.24 (red line); while for the 900 ºC QW sample, *n*=1.97 (blue line). For comparison, the underlying high-temperature-grown GaN templates (green line) has *n*~2. Herring showed that *n* values near 2 are consistent with a smoothing mechanism involving evaporation and recondensation of atoms on the surface. This leads to smoother surfaces with longer length scale features (1-10 µm). While *n* values near 4 are consistent with a smoothing mechanism involving surface diffusion [1], resulting in rougher surfaces with shorter length scale features (10-100 nm). The two smoothing mechanisms are summarized in Figure 3.

Finally, photoluminescence (PL) measurements reveal brighter emission from multiple quantum wells (MQWs) with barriers grown at 800 ºC compared to MQWs with barriers grown at 900 ºC, as seen in Figure 4. X-ray diffraction studies of these two samples find similar indium concentrations (~20%) and QW thicknesses for both MQWs, suggesting that the difference in emission intensity may be due to enhanced localization in QWs grown on the more textured 800 ºC barrier layers.

Our work provides evidence that changes in growth mechanisms can be used to control InGaN/GaN MQW morphology; moreover, the morphology may be linked to emission efficiency. However, the causal link between the MQW growth morphology and PL emission intensity awaits further study.

Reference

1. C. Herring, *J. Appl. Phys.* **21**, 301 (1950).

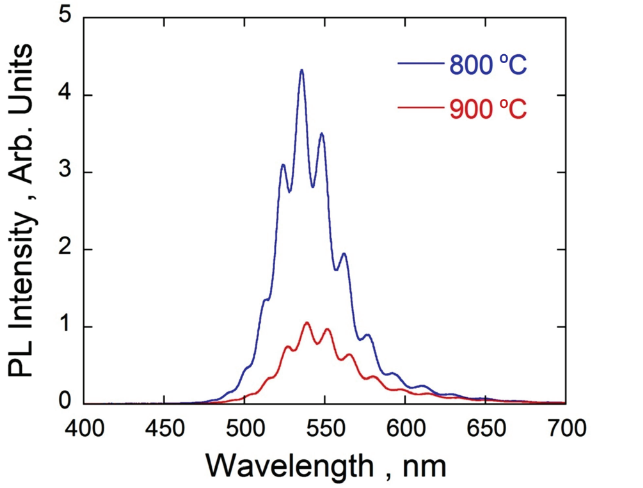

Figure 4: PL intensity for the two green light emitting MQWs shown in Figure 1 with GaN barrier temperatures of 800 ºC and 900 ºC.

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